AN INVESTIGATION OF COMBUSTION IN A FLOWING STREAM WITH TURBULENCE

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SUBMITTED TO THE FACULTY OF THE RENSSELAER POLYTECHNIC INSTITUTE IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

TROY, NEW YORK 16 JUNE 1947

ACKNOWLEDGMENT

The writer wishes to thank Professor Neil P. Bailey, of the Rensselaer Polytechnic Institute's Mechanical Engineering Department, and his associates for aid which, more than once, saved this undertaking from ignominious collapse.

Introduction

The state of present available knowledge of nuclear fission reactors is not yet sufficiently extensive to permit any detailed workable design of an atomic power plant for aircraft or guided missiles. Information on shielding requirements is particularly classified; therefore, this paper is concerned especially with applications in uninhabited missiles.

The aim of this paper is to review the nuclear fission process and its application in nuclear reactors. At the present time, the atomic pile is the most significant of the reactors and, therefore, it is covered as extensively as possible on the basis of a limited known theory. Finally, having investigated how power is produced from the nucleus, application is made to various foreseeable types of jet engines. An estimate is made of the characteristics of each type.

ABSTRACT

This thesis undertakes a general investigation of combustion in a flowing stream.

It was first necessary to determine, if possible, the mechanism of burning, to establish the flow characteristic which must be present for a flame to exist.

Study of an inverted flame was made in open air. The flame characteristics were observed by means of temperature and pressure surveys, schlieren photographs and smoke pictures.

Apparatus was constructed to allow burning in a flowing stream in a constant-area channel. Information gathered in the study of the inverted flame was applied to combustion in the constant-area channel.

Arrangement was made to preheat the air stream, and effects of stream temperature on burning velocity were noted.

This work is an attempt to reenforce combustion theory with experimental data. Many studies of this nature must be made before the mechanism of combustion is fully understood.

SYMBOLS USED

c - velocity of sound, ft. per sec. ($\sqrt{\gamma gRT}$)

C_v - specific heat at constant volume, Btu per lb. per deg. R.

C_p - specific heat of constant pressure, Btu per lb. per deg. R.

g - 32.2 ft. per sec. per sec.

M - Mach number ($\frac{V}{c}$)

P - absolute static pressure, lb. per sq. in.

P_o - absolute total pressure, lb. per sq. in.

R - gas constant, 53.3 for air

T - static temperature, deg. R.

T_o - total temperature, deg. R.

V - velocity, ft. per sec.

W - flow, lb. per sec.

Q - flow, cu. ft. per sec.

x - distance, in.

y - distance, in.

ρ - mass density, slugs per cu. ft.

γ - adiabatic gas constant, 1.395 for air at 540 deg. R. ($\frac{C_p}{C_v}$)

κ - adiabatic gas constant, 1.35 for air at 1960 deg. R.

δ - distance, in.

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INTRODUCTION

Combustion in a flowing stream is an extremely complicated chemical and mechanical process. There are so many variables, and their effects are so diverse, that a complete analytical solution has so far escaped the efforts of the many men working in this field.

The Bunsen Flame

Most of the fundamental work in the combustion field has been done with the Bunsen flame. With this flame it is possible to isolate and evaluate some of the variables. Others, such as the effect of turbulence and the mechanics of mixing, must be determined in other ways. The principles of the Bunsen flame are fundamental, however, and must be considered by any worker in the combustion field.

Definition of terms. Before proceeding with a discussion of the Bunsen flame, it is necessary to define and discuss the terms which will be used.[1]

Flame - gas rendered luminous by heating, or by the liberation of chemical energy.

Flame front - boundary surface between the luminous region and the dark region of unburned gas.

Reaction zone - region where homogeneous unburned charge is transformed into combustion products in chemical equilibrium.

Spatial velocity - velocity with which the flame

front moves in a direction normal to its surface, relative to a fixed point in the explosion vessel or exit port (must equal zero for a stationary flame).

Burning or transformation velocity - velocity at which the flame front advances into and transforms the unburned charge in a direction normal to its surface.

Mixture velocity - velocity with which mixture approaches flame front.

Gas velocity - velocity with which the flame is transported bodily in a direction normal to its surface as a result of the movement of the gas into which it is advancing. (For a stationary flame the gas velocity is the component of mixture velocity normal to the flame front, and is equal to the burning velocity in a stable front.

The Mechanism of Burning. For an ideal case, the gas mixture emerges from a burner tube whose wall offers no resistance to gas flow and neither absorbs nor conducts heat. If the mixture velocity is greater than the burning velocity, the flame front will take the form of a cone, the angle of which is such that the component of mixture velocity normal to the cone surface will at all times be equal to the burning velocity. If the mixture velocity is increased, the height of the cone will also increase, until a point is reached where the angle of the wall of the cone

with the stream direction nears zero, at which point combustion is no longer possible and the flame blows off. If the mixture velocity is decreased, the cone will shorten until the flame front becomes a plane surface, and will move down the tube as such. This will occur when the burning velocity exceeds the mixture velocity, and is called a flashback.

From this hypothetical flame it would be an easy matter to calculate burning velocity by measuring the mixture velocity and the cone angle. The actual flame, even with laminar flow, is not quite this simple. First, the velocity profile of the mixture is not uniform, but is influenced by friction in the tube. It varies according to

$$v = \bar{v}\,\frac{y}{\delta}\left(2 - \frac{y}{\delta}\right)$$

for laminar flow. The burning velocity is influenced also by the wall at the tube exit. Lewis and von Elbe[2] explain the mechanism in the following way, "A burner flame remains stationary above the orifice because there are regions, either near the rim or near an obstruction in the stream like the grid of a Meker burner, where the mixture velocity equals the burning velocity. These regions serve as continuous sources of ignition for the neighboring gas elements whose velocity exceeds the burning velocity. As the reaction zone propagates from these regions of equality, it assumes an angle to the direction of mixture flow so that everywhere the normal component (the gas velocity) of the mixture

velocity equals the burning velocity."

The burning velocity is influenced by the tube wall. The wall reduces the burning velocity by its quenching effect on the explosive reaction. This quenching effect is the result of the destruction of the chain carriers in the reaction, the wall acting as a third body. If the wall is cool, another effect is added. The chain carrier reactions require substantial activation energies, so if an energy loss is caused by the cool wall, the reaction, hence the burning velocity, will be slowed. As the wall is heated by the flame, this effect is lessened.[2]

As stated above, friction in the tube causes the mixture velocity to approach zero at the wall. There is usually some point, therefore, where the mixture velocity equals the burning velocity and a point of equilibrium is established. If the mixture velocity exceeds the burning velocity at all points, the flame will blow off; if the burning velocity exceeds the mixture velocity at all points, the flame will flash back.

An inverted flame is obtained by mounting a center rod in the tube. A region of low velocity is established in the wake of the rod. In this region a zone of equality of burning and mixture velocities

is formed at flow velocities which would exceed the critical for blowoff if the obstruction were not present. This flame takes the form of an inverted cone, with the apex in the vicinity of the center rod. Figure 3 is an example of an inverted flame. Quenching and cooling effects of the rod on the combustion reaction tend to hold the flame off the rod. As the rod is heated the flame tip moves closer, and if the rod becomes extremely hot the flame will attach itself and tend to move upstream along the rod. The inverted flame is very handy for use in experimental work, in that the flame front is not obscured by the rest of the flame zone.

A device which aids in establishing a flow zone of equal mixture and burning velocities is a flame holder. In most commercial applications of combustion to a flowing stream, a flame holder is necessary to allow the combustion to take place at high flow velocities.

Burning velocity. The burning velocity is of extreme importance in understanding the combustion reaction; it is therefore necessary to examine its properties and behavior.

Smith[3] concluded that for laminar flow, if the other variables are held constant, the burning velocity is a property of the fuel. He measured, for

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[illegible]

[illegible]

[illegible]

instance, the burning velocity of propane in air, with slightly excess fuel, and found it to be 1.65 ft./sec. He found that the burning velocity varied with the fuel-air ratio. Jost[4] determined that the burning velocity is relatively unaffected by external effects of pressure and temperature. He refers to work by Sachsse[5] which showed that it is necessary to preheat the mixture from 20° C. to 430° C. to double the burning velocity. Jost also concludes that the burning velocity is independent of the velocity of the mixture. If the increase of mixture velocity induces turbulence, however, the burning velocity appears to increase. The burning velocity probably remains constant, but the effective surface of action is increased, which has the effect of increasing the burning velocity. This was determined by Ubbelohde and Koelliker.[6]

<u>The Reaction Zone</u>. When an explosive mixture is ignited, combustion takes place in a narrow zone separating burned and unburned gas. This zone propagates itself into the unburned gas at the rate at which combustion reactions are induced in successive gas layers. This is the burning velocity. The reactions are induced by heat transfer (essentially conduction) and diffusion of active species.

In a laminar flame the reaction zone is very narrow, being on the order of .2 mm.[2] In a turbulent

flame the zone is wider and of a more complicated structure, in that some unburned gas is able to pass through it without being acted upon sufficiently by conduction and diffusion to enter into the reaction. This unburned gas usually forms a backflow or eddy, eventually entering into the reaction in the region of the ignition point. This aids in the maintenance of a stable flame in turbulent flow.

The rates of conduction and diffusion determine the burning velocity. The conduction process must raise the mixture to the ignition temperature. This is the reason that preheating is of some aid in increasing the burning velocity.

Turbulence. In passing, several references have been made to effects of turbulent flow on the flame. Very little information is available in the literature on this subject. Most references are merely to the effect that certain fundamentals established in laminar flow do not seem to hold for turbulent flow. One of the aims of this paper is to investigate the flame in turbulent flow and to attempt to draw conclusions as to how practical it is to apply the fundamentals of laminar flow flames to the turbulent flame.

Some points concerning the turbulent flame have been brought out in the literature, however. Jost

and others have suggested the passage of unburned gases through the flame front and a resultant back eddy into the region of ignition. As mentioned before, turbulence has the effect of increasing the net burning velocity. Turbulence also aids in establishing an ignition point by slowing the flow of the unburned mixture.

Combustion in a Tube

Ideal flame. In a tube, the ideal flame (laminar flow, no wall effects) would form a plane surface across the tube and would remain stable at one point in the tube if the mixture velocity exactly equalled the burning velocity. If the mixture velocity was increased or decreased, the flame front would move up or down the tube. Actually, of course, the situation is quite different. The case for laminar flow will be considered first.

It would appear logical to set up the flow conditions in the tube and evaluate the combustion mechanism from the burning velocity and the flow conditions of the unburned mixture. Unfortunately, the problem has not been treated in this manner in the literature. In order to make use of other work in the field[4] the problem will be stated in the reverse form; i. e., a plausible form of burning surface will be assumed and an attempt made to gain an insight into the flow conditions.

A new term must now be added to the list of definitions: the flame velocity is defined as the velocity with which the entire flame front is moving into the unburned mixture parallel to the tube wall. For a flame stationary in the tube, flame velocity will equal the average mixture velocity.

The most reasonable flame front shape to assume is a paraboloid. Since the paraboloid surface is 1.86 times that of the tube cross section, the flame velocity must be 1.86 times the burning velocity. At the tube center, where the flame front is normal to the tube axis, the velocity of combustion must be equal to the burning velocity; therefore, an added forward flow, 0.86 times the burning velocity, is required to obtain the flame velocity 1.86 times the burning velocity. Progressing toward the wall, this factor becomes smaller until the point is reached where the flame velocity equals 1.86 times the burning velocity. From this point outward to the wall, the burning velocity is greater than the effective flame velocity and an additional flow must be established in the other direction. Obviously, these additional flows must come from changes in the flow of unburned gas. It is observed that the unburned mixture decelerates in the center of the tube and accelerates near the wall to satisfy

these conditions.[4] Experimental results have shown the flame velocity to be at least double the burning velocity, which compares favorably with the assumed value of 1.86.[8]

Cooling effect. Adding the cooling effect of the wall, which would result in a lowering of the burning velocity near the tube, the form of the flame surface toward the rim would be quite different from the assumed paraboloid. As the burning velocity approaches zero, which it does in an actual burner, the practical result is that a certain finite layer of the mixture is not reached by the flame front at all. This gas will pass the flame front and react among the burning gases behind the flame front. But as the tube wall is heated by a stable flame, the cooling effect is diminished, and as the temperature of the wall reaches the ignition point, a region of ignition is formed which tends to anchor the flame.

Velocity Profile. When the velocity profile of the unburned gas is added to the above case, it becomes quite complicated. The flame shape tends to flatten out, if not reverse, and the accelerations and decelerations in the unburned mixture change considerably. It was noted experimentally, however, (to be discussed in a later chapter), that the flame formed in a pipe, with a center tube mounted coaxially, very closely resembles the inverted flame, to which the above principles will apply.

Combustion with Flow

The rise in burning velocity, and the consequent increase in flame velocity, brought about by pre-heating, has appeal to the idea of burning fuel injected into a flowing air stream in a constant-area channel for the purpose of increasing the flow velocity.

The simplest case[9] involves heating at a constant flow area at such a rate that the resultant pressure change is large enough to allow the neglect of friction over the length involved. The entire pressure change may then be assumed to be a result of the acceleration made necessary by the volume change.

$$dP = -\rho v \, dv$$

For constant-area, steady flow,

$$\rho v = \rho_1 v_1 = \rho_2 v_2 = \text{constant}$$

so

$$\int_{P_1}^{P_2} dP = -\rho v \int_{v_1}^{v_2} dv = -\rho v (v_2 - v_1)$$

giving

$$P_2 - P_1 = \rho_1 v_1^2 - \rho_2 v_2^2 = \gamma P_1 M_1^2 - \gamma P_2 M_2^2$$

This may be written,

$$\frac{P_1}{P_2} = \frac{1 + \gamma M_2^2}{1 + \gamma M_1^2}$$

which is the equation of a Rayleigh line. This equation defines any pressure change which occurs

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[illegible]

[illegible]

$$[illegible]$$

$$[illegible]$$

[illegible]

$$[illegible]$$

[illegible]

at constant area with no friction.

For constant area and steady flow,

$$\frac{P_2}{\sqrt{T_{o_2}}} M_2 \sqrt{\frac{\gamma g}{R}\left[1 + \frac{\gamma - 1}{2} M_2^2\right]} = \frac{P_1}{\sqrt{T_{o_1}}} M_1 \sqrt{\frac{\gamma g}{R}\left[1 + \frac{\gamma - 1}{2} M_1^2\right]}$$

divide by the Rayleigh line equation to eliminate P_1 and P_2 gives,

$$\frac{M_2 \sqrt{\frac{\gamma g}{R}\left[1 + \frac{\gamma - 1}{2} M_2^2\right]}}{1 + \gamma M_2^2} = \sqrt{\frac{T_{o_2}}{T_{o_1}}} \; \frac{M_1 \sqrt{\frac{\gamma g}{R}\left[1 + \frac{\gamma - 1}{2} M_1^2\right]}}{1 + \gamma M_1^2}$$

This equation makes it possible to predict the final Mach number (M_2) that results when flow at constant area and initial Mach number (M_1) is heated through a total temperature ratio ($\frac{T_{o2}}{T_{o1}}$) without friction.

Equation 1 is plotted in figure 6. Implications from figure 6 are that heating subacoustic flow will increase the Mach number, and that heating superacoustic flow will decrease the Mach number. It is worthy of note that a subacoustic flow cannot become superacoustic by the addition of heat, but will always approach the acoustic.[10] Similarly, the superacoustic flow cannot become subacoustic, but will again approach the acoustic state. This confirms the stability of the acoustic state, which can be predicted as it is a condition of greatest entropy.[11]

DESCRIPTION OF EQUIPMENT

Two sets of equipment were used for these experiments: a constant-area burner and an inverted-flame apparatus.

Constant-area burner. For the constant-area burning work the apparatus pictured in figures 1 and 2 was used. A model 210 Schramm single-stage, motor-driven, direct-connected compressor served as the air supply, delivering a maximum of 175 cubic feet per minute of air at 80 pounds per square inch, gage, pressure. Air was delivered by a one-inch line, in which a gate-type control valve was located. This gate valve was bypassed by a quarter-inch line containing a needle valve for fine adjustment of air flow.

Air entered the equipment through the pre-heat burner. This burner had been constructed in the research laboratory of the General Electric Company for work with liquid fuels. A new fuel nozzle was constructed so the burner could be used with propane gas fuel. Theoretically, this burner will deliver exhaust products at 1000° F., with enough excess air to allow complete combustion in the constant-area burner downstream. During this work, however, the fuel nozzle was never in proper adjustment, and 500° F. was the best temperature which

could be obtained with enough air and oxygen in the exhaust products for burning downstream. This temperature and air flow were adequate, however, for the tests made.

The burner was constructed so that air entered the combustion region through holes in the burner liner. The fuel was delivered radially at the nose of the burner liner. When in proper operation, the flame front stood about half-way down the liner. Ignition was furnished by a spark plug set in the burner wall at the downstream end of the liner. Current for the spark was obtained from a Variac adjustable transformer, type 100Q.

Air left the pre-heat burner through a half-inch section, then expanded into a measuring chamber of two-inch diameter. In this chamber the air slowed to a very low velocity. Temperature was measured at this point by means of an unshielded Chromel-alumel thermocouple (diameter: one-tenth inch) inserted in the stream. Pressure, total and static, was also measured, with an impact tube and wall taps.

Leaving the measuring section, the air was accelerated through a nozzle into a one-inch pipe section. Three static wall taps were located in this section, at the nozzle throat, and at two-inch intervals down the pipe. An unshielded Chromel-alumel thermocouple was mounted in the tube near the down-

stream end.

This one-inch pipe section acted as a constant-area burner. Fuel was delivered to a point between the first two pressure taps by a center tube which was held at the upstream end by a bracket in the measuring chamber. The center tube was standard quarter-inch steel tubing. Fuel entered the air stream from the center tube through eight radial holes of .04-inch diameter. The upstream end of the tube was blocked off.

Ignition in the constant-area burner was obtained by a small spark plug mounted in the burner wall. This plug is of the type used in model airplane engines. Current for spark was furnished by transformer.

Commercial bottled propane gas was used as fuel. Each tank contained 852 cubic feet of gas, a net weight of 100 pounds. Lower heating value was 18,700 BTUs per pound. Ratio of specific heats is 1.153 at room temperature.

The fuel system consisted of a tank of propane gas with a standard acetylene-type reducing fitting mounted at the exit valve. Quarter-inch copper tubing carried the fuel to a tee fitting located near the burners. Two needle valves were mounted after the tee to control fuel flow to the two burners. Fuel was delivered from the control valves to the

burners by copper tubing. Proper adjustment of the master control valve at the tank and the needle valves would result in a steady fuel pressure to either or both burners. At low fuel pressures, however, the system was somewhat pressure-sensitive.

Fuel flow was determined by calibrating the system against line pressure. Pounds per second of fuel delivered against a fixed pressure are plotted versus line pressure (figure 5).

Air pressure measurements were made by water manometers and inclined-draft gage. Air flow was computed across the two-inch to one-inch area reduction.

Inverted flame equipment. The equipment used in studies of the inverted flame was constructed by Lt. Comdr. J. P. Field Jr., USN, for his work on flame holders. The apparatus is pictured in figure 4.

Air supply was furnished by a centrifugal blower rated at 175 cubic feet per minute. The original motor had been replaced, however, so that the actual output was considerably below that figure. Air was delivered at a constant pressure of 26 inches of water, gage.

Air metering was accomplished with a flat orifice plate constructed and installed according to specifications of the American Society of Mechanical Engineers.[7] The orifice was installed in a three-inch brass pipe. Orifice diameter was 1.531 inches.

Pressure taps were installed one-half inch on either side of the orifice plate. Differential pressure across the orifice was measured with an inclined manometer which could be read to a hundredth of an inch of water. Weight flow measurements should be accurate within three per cent.

Mixture flow was controled by a three-inch gate valve installed twenty-five inches downstream from the metering orifice and nine inches downstream from the point of fuel injection. This valve allowed control of flow within less than 0.005 inches of water on the differential manometer. The location of this valve also aided in mixing the air and fuel.

The fuel system was similar to that used on the constant-area burner. Commercial bottled propane gas was used, with the tank fitted with the standard acetylene-type reducing valve. Quarter-inch copper tubing carried the fuel to a needle control valve mounted on the apparatus. The fuel was injected into the air stream by a curved tube pointing upstream.

After leaving the control valve, the mixture of air and fuel passed through a three-to-one reducing fitting and entered a section of one-inch pipe. The one-inch pipe section was three feet long. Inside the pipe a quarter-inch steel rod was mounted coaxially,

and held in place by two sets of three set-screws, located one foot and two feet from the downstream end of the one-inch pipe. A rod with a rounded end was used for most of the experiments, but for several a flat-ended rod was substituted. The rod protruded about one-half inch from the end of the one-inch pipe.

Temperature and pressure measurements. A sliding rack device to which was attached a Chromel-alumel thermocouple was used for a temperature survey of the flame. Two scales were attached to the rack: the X scale, which was calibrated to one-sixteenth of an inch, was used to measure the distance in the line of flow downstream from the end of the rod; the Y scale, which was calibrated to thousandths of feet, was used to measure distances from the rod normal to the line of flow. Temperature in millivolts was read on a standard galvanometer manufactured by the General Electric Company.

A pressure survey was made by replacing the thermocouple with an impact tube of one-tenth inch diameter. Total pressures were read on an inclined manometer, which gave accurate readings to one-hundredth of an inch water, gage.

Smoke photography. Smoke pictures of the inverted flame were taken with a 2¼ by 3¼ Graphlex camera equipped with a Kodak anastigmat f 4.5 lens. Shutter speed

of one-tenth second and lens aperture of f 4.5 were used with Kodak Tri-X panchromatic film, film speed Weston 200. Illumination was by one General Electric Photoflood No. 2 placed three feet from the flame. Lt. Comdr. Field collaborated in obtaining these pictures.

Schlieren photography. The Schlieren studies of the inverted flame were made by Capt. Russell Herrington, U. S. Army Air Forces. Illumination was by spark, exposure time one-thirty-thousandth of a second.

THE EXPERIMENT

The experiment divides itself roughly into two parts: investigations of the inverted flame burning in the open air to determine the general properties of a turbulent flame, and studies of the flame confined in a constant-area tube.

The Inverted Flame. A temperature survey of the inverted flame was made to determine the location of heat concentration and position of the reaction zone. Results of this survey are shown in figure 8. Average mixture velocity was 24.3 feet per second, and the mixture a little on the rich side of the stoichiometric point. The presence of the thermocouple tended to disturb the flame, but by using care in the handling of the apparatus this effect was minimized. In general, the results can be classified as rough. Some temperature measuring device such as the sodium line reversal method would yield much more accurate results. Reasonably sound quantitative conclusions can, however, be drawn from figure 8.

The pressure survey was made in an attempt to determine the total pressure changes taking place in the neighborhood of the reaction zone. The stream

was first surveyed with an impact tube, without the flame. The isobars are plotted as full lines in figure 9. The flame was then lighted, keeping the mixture velocity the same, and a survey was made of the flame. These results were very inconclusive. The readings obtained scattered when plotted. This indicated that experimental errors had overshadowed the small differences in pressure which must be measured in order to draw the proper conclusions. Enough points, however, appeared consistent to plot three isobars, one in front of the flame front and two behind it. These isobars are plotted in figure 9 as broken lines. The position of the flame front was determined by observation and is plotted in figure 9 as a double broken line.

Two photographs of the inverted flame were taken with smoke added externally at the exit of the pipe. Figure 3 shows the flame burning with the stream velocity about 50 feet per second. Figure 10 is a flame burning with the stream velocity about 25 feet per second. The luminous flame front is clearly outlined. The smoke pattern defines the outer edge of the mixture stream. Figure 11 is a plot of the flame and stream limits. The flame of figure 10 is representative of the flame used in the temperature and pressure surveys.

Schlieren photographs (figures 12 and 13) were made of the above flames. The 50-feet-per-second flame (figure 13) shows plainly the limit of the flame

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front and the limit of the mixture stream. Variations in the flame front, which do not appear in the smoke picture, are visible. The low velocity schlieren photograph (figure 12) also defines the flame front and mixture boundary. In addition, some indication of flow conditions at the end of the rod is given. The Schlieren photograph (figure 14) of the mixture stream without the flame indicates the extent of mixing and diffusion with the outside air.

Photographs of the flame were taken on infra-red film. Mixture velocity was 25 feet per second. A red filter was used to exclude all light except from the red end of the spectrum. This photograph is shown in figure 15. It was taken to see how much, if any, of the reaction zone lies ahead of the visible flame front.

The Constant-Area Burner. Experiments were conducted on the constant-area burner 1) pre-heating the air, 2) without pre-heating the air, and 3) injecting the fuel through the pre-heat burner but burning only in the constant-area burner.

Primary purpose of the experiments was to determine the rise in Mach number resulting from constant-area burning. Early results indicated, however, that a stable flame could not be maintained in the constant-area burner at entering Mach numbers above .05. Method and procedure, therefore, were varied and results were checked against theory.

For a test with pre-heated air, the pre-heat burner was lighted off and air flow set at a predetermined value of total pressure. Temperature (T_{o_1}) was then adjusted to the desired reading by varying the fuel flow. Minor adjustments of air and fuel were made to insure smooth burning. The constant-area burner was then lighted off and a stable flame obtained by adjustment of the fuel supply. Necessary readings were made. Air flow was then increased or decreased and the system balanced again by adjustment of the two fuel systems. Flame stability and smooth burning were the guides used in the setting of the fuel-air ratios. Calculations proved that smooth burning occurred in every case somewhat on the rich side of the theoretical stoichiometric mixture.

For the non-pre-heating tests the method was similar, but simplified by the elimination of the pre-heat burner.

From the readings taken in these tests, values of M_3 and M_5 were calculated as shown in tables IV and V. A theoretical M_5 was then calculated from figure 6-A. Unfortunately, the successful runs were at such a low flow that accuracy of the pressure readings is questionable.

In the mixing and burner loss tests the center tube fuel line was removed from the constant-area burner. Fuel was injected through the pre-heat burner, thoroughly mixed in passing through the measuring cham-

ber and burned at the usual point in the constant-area burner. Total pressure readings were taken at points 1 and 5, with the burner on and with the burner off, in order to determine friction and burner pressure losses. The friction loss was subtracted from the total loss to determine burner loss. (See table VI.) One run was made just below blow-off and one just above flashback so that the effect of premixing fuel and air could be determined by comparing these figures with those for the tests where premixing was not used.

The flame was observed during the constant-area burner runs in a mirror mounted off the end of the burner. This helped in determining the location and shape of the flame front, and observations of flame color gave some indication of certain chemical phenomena.

RESULTS

The reaction zone in the turbulent flame is a narrow region, bordering the flame front, where the major portion of the temperature rise and chemical reaction occurs. The temperature survey (figure 8) shows this zone to be less than a tenth of an inch across. This is wider than the Lewis and Von Elbe[2] figure of 0.2 mm. for the laminar flame, but is of the same order of magnitude. Farther down the flame, where the flame front breaks up because of increased turbulence, the reaction zone is not well-defined and reaction takes place in turbulent balls (figure 12).

A drop in total pressure occurs across the reaction zone. The pressure survey (figure 9) shows a change from 0.10 inches water, gage, to 0.07 inches water, gage. A comparable run in the constant-area burner (run 5, table VI) gives a change from 0.13 inches of water, gage, to 0.11 inches of water, gage. It seems apparent, therefore, that burner pressure losses are the result of the total pressure loss across the flame front.

The flame front is irregular. Schlieren photographs (figures 12 and 13) show turbulence. Curvature of the flame front can be seen in the smoke and schlieren photographs. There is an interrelation between this curvature, turbulence, burning velocity and mixture velocity. Turbulence increases in the downstream direction (figures 12 and 13); therefore, the burning velocity increases.

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As the burning velocity increases, the curvature increases. On the other hand, the mixture velocity is decreasing (figure 11) in the downstream direction. This also results in an increase in curvature. The curvature increases until the angle of the flame front to the stream direction becomes so large that the flame front breaks up into unstable, turbulent balls (figure 12), within which the remaining reaction takes place.

The photographs show that the flame does not adhere to the end of the rod, but forms slightly off the end. This is because of the quenching and cooling effect of the rod. The temperature survey (figure 8) indicates a cool region (1500° F.) in the flame at its tip, just off the end of the rod. This shows that the temperature reached in the reaction zone is influenced by quenching and cooling. But as the rod heats up the flame moves closer, until eventually the flame adheres to the rod. As the rod is progressively heated the flame tends to move upstream along the rod. When the flame adheres to the rod the critical mixture velocity for blow-off increases, indicating that the burning velocity in the ignition region has been increased.

The ignition zone forms at a point where the mixture velocity and the burning velocity are equal. This zone locates itself in the wake of the rod, because that is a region of low mixture velocity. Heating of the rod decreases the cooling and quenching effects, thereby increasing the burning velocity.

In the constant-area burner the ignition zone will form behind the slightest obstruction in the stream (a piece of piano wire wrapped around the center tube, or the spark plug wire), or at a hot spot on the tube wall. If all obstructions are removed, and the wall is not hot, the flame becomes unstable. Blow-out and flashback points are very close together; in fact, the flame will go either way with the same flow. But as soon as a hot spot on the wall develops the ignition zone will anchor to it; then the flow can be doubled without blow-out occurring.

The infra-red photograph contains no additional information. Apparently all of the reaction is indicated on the smoke and schlieren photographs.

The constant-area burner tests resulted in a rise in Mach number across the flame zone. From tables IV and V it can be seen that the actual rise in Mach number was somewhat less than the theoretical increase computed from figure 6-A. The extremely low flows at which successful runs could be made make the pressure readings suspect. The wall taps had not been designed to handle such low pressures, so it is felt that the difference between actual and theoretical Mach number after burning is well within experimental error.

The extremely low flows at which blow-out occurred were disappointing. A check with theory, however, shows that they were to be expected. About ten feet per second was the maximum mixture velocity at which the flame could

[illegible]

[illegible]

[illegible]

[illegible]

be held in the tube with no obstructions or hot spots. From theory the flame velocity can be predicted to be in this range. A small obstruction will allow a doubling of the mixture velocity.

Some mixing length is necessary. Fuel injection was two inches and spark ignition one inch upstream from point 4, but the pressure drop always occurred between point 4 and point 5. The critical mixture velocity for blow-out was increased somewhat by thorough mixing upstream, but not significantly. This indicates that adequate mixing can be accomplished in a turbulent stream in a short distance.

There is indication that some of the mixture passes through the reaction zone without reacting. This unburned mixture forms a counter-flow within the flame zone toward the ignition zone. This counter-flow can be seen in the schlieren photograph, figure 12. It was also apparent visually.

Contrary to assumption, blow-out occurred at a lower approach Mach number using pre-heated air than without pre-heating. During the pre-heated runs the nose indicated the possibility of incomplete combustion. Evidently there was not enough air and oxygen in the products of the pre-heat burner to allow complete combustion downstream. In fact, if the temperature of the pre-heat burner was doubled, combustion could not be maintained downstream at all.

CONCLUSIONS

It can be concluded that while turbulence plays a marked part in the mechanics of combustion, the theories which are available in the literature concerning the laminar flame are in many cases applicable to the turbulent flame as well.

The establishing of an ignition zone is necessary for stable combustion. This ignition zone must be a region of low velocity and divorced as much as possible from quenching and cooling effects. The maintenance of a stable ignition zone will be aided by a back-flow of unburned mixture which passes through the flame front without reacting.

The results shown in tables IV and V indicate that an increase in Mach number is obtained across the flame zone. The apparatus used in the experiments must be redesigned, however, if more satisfactory results and higher Mach numbers are to be obtained. Much higher pre-heat temperatures must be used, and these temperatures obtained in such a way that sufficient air is available in the constant-area burner for complete combustion.

RECOMMENDATIONS FOR FURTHER STUDY

If the flow conditions within a turbulent flame and the conditions required by the flame of the approaching flow could be analyzed, burner design would be simplified.

Experimental work should be done on a larger burner than the one used for this project. Instrumentation must be more sensitive, and facilities designed for taking accurate temperature and pressure measurements at any point in the tube.

The study of the increase in Mach number across a flame front in a constant-area channel depends to a large extent on pre-heating the air. Pre-heating to 1000° F. should double the burning velocity from the room temperature figure. Some method of pre-heating must be devised which does not limit the quantity of air in the constant-area burner. Possibly some sort of heat exchanger can be worked out.

Results of work of this nature could well be applied to the design of flame holders. Once the flow requirements of a flame are understood, channel shape and obstruction characteristics can be designed to satisfy these requirements.

APPENDIX

TABLES AND CALCULATIONS

TABLE I

TEMPERATURE SURVEY
Inverted Flame

$\Delta h = .05'' \ H_2O$

gas pressure = 2 lbs/sq. in.

Temperatures were taken with Chromel-Alumel thermocouple.

X is distance in direction of flow

Y is distance normal to flow

Zero position:

X = 12.688 inches

Y = 1.744 feet

1.

Y in feet	X in inches	Temperature in millivolts
1.744	17.0	44.0
	16.0	45.2
	15.0	45.6
	14.0	45.6
	13.5	44.9
	13.25	43.7
	13.00	41.4
	12.875	38.1
	12.814	36.6
	12.750	34.8

2.

Y in feet	X in inches	Temperature in millivolts
1.760	20.875	11.0
	18.0	13.9
	17.0	42.4
	16.0	44.4
	15.0	44.7
	14.0	45.8
	13.5	45.9

3.

Y in feet	X in inches	Temperature in millivolts
1.770	19.0	25.8
	18.0	35.2
	17.0	41.7
	16.0	44.4
	15.0	45.8
	14.0	46.7
	13.5	40.7
	13.25	26.0
	13.0	16.0

4.

Y	X	T
1.780	19.0	20.0
	18.0	33.8
	17.0	42.1
	16.0	43.9
	15.0	45.3
	14.5	46.4
	14.0	45.6
	13.5	29.2
	13.0	10.8

5.

Y	X	T
1.790	19.0	22.9
	18.0	34.4
	17.0	40.9
	16.0	43.0
	15.0	44.5
	14.5	44.5
	14.0	39.8
	13.5	16.6

6.

Y	X	T
1.93	11.0	2.86
1.92	11.0	1.7
1.91	11.0	1.2
1.90	11.0	5.0
1.89	11.0	5.86

7.

Y	X	T
1.90	11.25	6.25
1.91	11.25	4.0
1.92	11.25	2.6

8.

Y	X	T
1.92	11.5	2.17
1.91	11.5	5.3
1.90	11.5	21.2

9.

Y	X	T
1.94	11.75	10.0
1.93	11.75	9.65
1.92	11.75	17.0
1.91	11.75	34.9

TABLE II

PRESSURE SURVEY
Without Flame

Δh = .05" H_2O

barometer = 30.07 in. Hg

Pressures were taken with impact tube

X is distance in direction of flow

Y is distance normal to flow

Zero position:

X = 14.25

Y = 1.825

1.

X in inches	Y in feet	P_o in inches H_2O
14.25	1.825	0
	1.830	0
	1.835	.105
	1.840	.150
	1.845	.162
	1.850	.166
	1.855	.158
	1.860	.149
	1.865	.119
	1.870	.055
	1.875	.020
	1.880	.010
	1.885	.009
	1.890	.008

2.

X	Y	P_o
15.25	1.890	.007
	1.880	.018
	1.870	.040
	1.860	.092
	1.850	.141
	1.840	.163
	1.835	.150
	1.830	.130
	1.825	.112

3.

X	Y	P_o
14.75	1.825	.073
	1.830	.114
	1.835	.150
	1.840	.160
	1.845	.163
	1.850	.161
	1.855	.149
	1.860	.118
	1.870	.050
	1.880	.014
	1.890	.008

4.

X	Y	P_o
16.25	1.890	.010
	1.880	.018
	1.870	.037
	1.860	.064
	1.850	.120
	1.840	.149
	1.830	.146
	1.825	.138

TABLE III

PRESSURE SURVEY
With Inverted Flame

Δh= .05 in. H_2O

Barometer= 30.07 in. Hg
gas pressure= 1.5 lbs/sq. in.

Pressures were taken with impact tube

X is distance in direction of flow

Y is distance normal to flow

Zero position:

X = 14.25

Y = 1.825

1.

X	Y		P_o
15.25	1.890		.025
	1.880		.070
	1.860	(in flame front)	.120
	1.840		.050
	1.830		.045
	1.825		.043
	1.850		.064

2.

X	Y		P_o
16.25	1.890		.049
	1.880	(in flame front)	.055
	1.870		.050
	1.860		.043
	1.840		.090
	1.825		.075
	1.850		.090

3.

X	Y		P_o
14.75	1.880		.080
	1.860		.060
	1.850		.100
	1.840	(in flame front)	.075

3. (con't.)

X	Y	F_o
14.75	1.830	.90
	1.825	.215

4.

X	Y	F_o
14.50	1.860	.070
	1.840	.075
	1.830	.060

TABLE IV

HEATING IN CONSTANT-AREA BURNER

(Mach Number Tests, pre-heated)

For subscripts on pressure and temperature readings, refer to figure 2.

Barometric pressure = 30.03" Hg

Temperature compressor air = 80° F.

Cold junction = 75° F.

Pressure in inches water

Temperature in millivolts

Run No.	P_{o1}	P_3	P_4	P_5	P_{o5}	T_{o1}	T_{o2}
1	1.2	.90	1.0	.60	1.0	13.0	36.0
2	1.3	.90	.90	.60	1.1	13.0	32.0
3	1.3	.90	.90	.60	1.1	12.8	33.0

Sample calculation:

P_o = 30.03" Hg = .491 x 30.03 = 14.7447 lbs/in.^{2} abs.

P_{o1} = 1.2" H_2O = .0361 x 1.2 = .0433 lbs./in.^{2} gage

P_{o1} = 14.745+.0433 = 14.788 lbs./in.^{2} abs.

P_3 = .9" H_2O = .0361 x .9 = .0325 lbs./in.^{2} gage

P_3 = 14.7447 + .0325 = 14.777 lbs./in.^{2} abs.

$P_4 = 1.0"H_2O = .0361 \times 1.0 = .0361$ lbs./in.^{2} gage

$P_4 = 14.7447 + .0361 = 14.781$ lbs./in.^{2} abs.

$P_5 = .6"H_2O = .6 \times .0361 = .02165$ lbs./in.^{2} gage

$P_5 = 14.7447 + .02165 = 14.7664$ lbs./in.^{2} abs.

$P_{o_5} = 1.0"H_2O = .0361 \times 1.0 = .0361$ lbs./in.^{2} gage

$P_{o_5} = 14.7447 + .0361 = 14.781$ lbs./in.^{2} abs.

$$\frac{P_{o_1}}{P_3} = \frac{14.788}{14.777} = 1.00074$$

$$M_3 = \frac{2}{K-1}\left[\left(\frac{P_{o_1}}{P_3}\right)^{\frac{K-1}{K}} - 1\right]$$

where average K = 1.35

$$M_3 = .0326$$

$$\frac{P_{o_5}}{P_5} = \frac{14.781}{14.766} = 1.00102$$

$$M_5 = .0381$$

M_5, theoretical, from figure 6-A

for $M_3 = .0326$

$f(M_3) = .0295$

$$\sqrt{\frac{T_{o_2}}{T_{o_1}}} = \sqrt{\frac{2190}{1110}} = 1.406$$

$f(M_5) = .0295 \times 1.406 = .0414$

from figure 6-A

$M_5 = .0460$

This data was taken just below blow-off, and represents maximum results obtainable from the equipment.

Accuracy of pressure measurements is doubtful in this range.

Pressures in pounds/square inch, absolute

Temperatures in degrees Rankine

Run	P_{o_1}	P_3	P_4	P_5	P_{o_5}	T_{o_1}	T_{o_2}
1	14.788	14.777	14.781	14.7664	14.781	1110	2190
2	14.792	14.777	14.777	14.7664	14.784	1110	1920
3	14.792	14.777	14.777	14.7664	14.784	1102	1960

Run	$\frac{P_{o_3}}{P_3}$	$\frac{P_{o_5}}{P_5}$	M_3	M_5	M_5 theoretical
1	1.00074	1.00102	.0326	.0381	.0460
2	1.00100	1.00120	.0380	.0420	.0510
3	1.00100	1.00120	.0380	.0420	.0510

TABLE V

BURNING IN CONSTANT-AREA BURNER

(Mach Number Tests - No Pre-heat)

For subscripts on pressure and temperature readings, refer to figure 2.

Barometric pressure = 29.77"Hg

Total temperature (T_{o_1}) = 90° F.

Cold junction = 75° F.

Pressure in inches water

Temperature in millivolts

Readings taken at blow-off

Run No.	P_{o_1}	P_3	P_5	P_{o_5}	T_{o_1}	T_{o_2}
1	1.9	1.4	1.0	1.70	.2	42.5
2	1.9	1.5	1.0	1.70	.2	43.5
3	1.9	1.5	1.0	1.70	.2	46.0

Run No.	P_{o_1}	P_3	P_5	P_{o_5}
1	14.68567	14.66757	14.65317	14.67847
2	14.68567	14.67127	14.65317	14.67847
3	14.68567	14.67127	14.65317	14.67847

Run No.	T_{o_1}	T_{o_2}	$\frac{P_{o_1}}{P_3}$	$\frac{P_{o_5}}{P_5}$	M_3	M_5	M_5 theoretical
1	550	2400°	1.00123	1.00173	.0430	.0496	.090
2	550	2440	1.00098	1.00173	.0374	.0496	.080
3	550	2560	1.00098	1.00173	.0374	.0496	.082

TABLE VI

BURNING IN CONSTANT-AREA BURNER
(Mixing and Burner Loss Tests)
For subscripts on pressure and
temperature readings, refer to
figure 2.

Barometric pressure = 29.94" Hg
Total temperature (T_{o_1}) = 80° F.
Cold junction = 75° F.

Pressures in inches of water
Temperatures in millivolts

Burning

Run No.	P_{o_1}	P_{o_5}	P_3	T_{o_2}
1	.8	.4	.55	33.0
2	1.0	.6	.70	32.0
3	1.2	.75	.85	31.0
4	1.4	.85	.90	31.0
5	.13	.11	.10	———
		No Burning		
1a	.2	.1	.07	0.4
2a	.25	.15	.10	0.4
3a	.26	.20	.10	0.4
4a	.27	.21	.10	0.4

Run No.	P_{o_1}	P_{o_5}	P_3	$P_{o_1}-P_{o_5}$	M_3
1	14.72942	14.71498	14.72040	.01444	.0295
2	14.73664	14.72220	14.72561	.01444	.0326
3	14.74386	14.72761	14.73122	.01625	.0352
4	14.75108	14.73122	14.73279	.01986	.0430
5	14.70524	14.70451	14.70415	.00073	.0096
1a	14.70776	14.70415	14.70307	.00361	.0214
2a	14.70956	14.70595	14.70415	.00361	.0231
3a	14.70992	14.70776	14.70415	.00216	.0238
4a	14.71028	14.70812	14.70415	.00216	.0246

	$P_{o_1} - P_{o_5}$ (Corrected for friction)
1	.01083
2	.01083
3	.01409
4	.01770

Run No. 4 taken just below blow-off

Run No. 5 taken just above flashback

TABLE VII

CALCULATION OF VELOCITY FROM VOLUME FLOW

(Inverted Flame Tests)

Pipe diameter - 3 inches

Orifice diameter - 1.531 inches

$$\frac{\text{Orifice diameter}}{\text{Pipe Diameter}} = \beta = \frac{1.531}{3} = .5103$$

(from "History of Orifice Meters and the Calibration, Construction and Operation of Orifices for Metering," A. S. M. E., 1935)

for average $R_D = .0562 \times 10^6$

and $\beta = .5103$

$K = .624$

where

$K = M\,C$

$Q = Y\,M\,C\,A\sqrt{2\,gh}$

where

Y - compressibility factor

M - velocity of approach factor

C - coefficient of discharge

A - orifice throat area

h - difference of head in feet

(from Mark's Handbook, page 2098, figure 16)

$$Y = 1$$

and, if

$$K\,C = .624$$

and

$$A = .0126 \text{ square feet}$$

then

$$Q = .0641 \sqrt{\Delta h} \text{ in cubic feet/second}$$

$$v = \frac{Q}{A} = \frac{.0641 \sqrt{\Delta h}}{.00592}$$

$$v = 10.65 \sqrt{\Delta h} \text{ feet/second}$$

plotted on figure 7

FIGURES

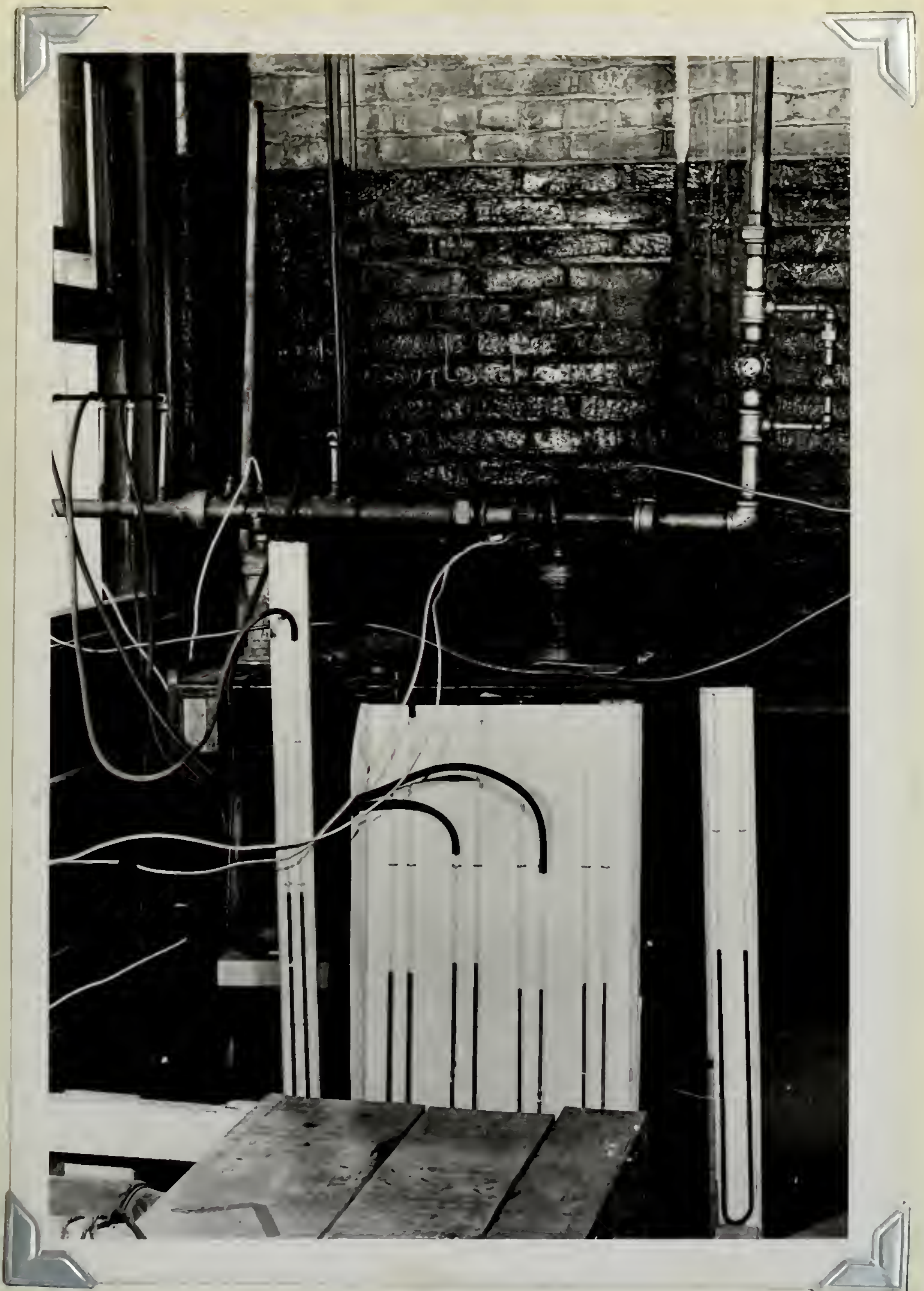


FIGURE I

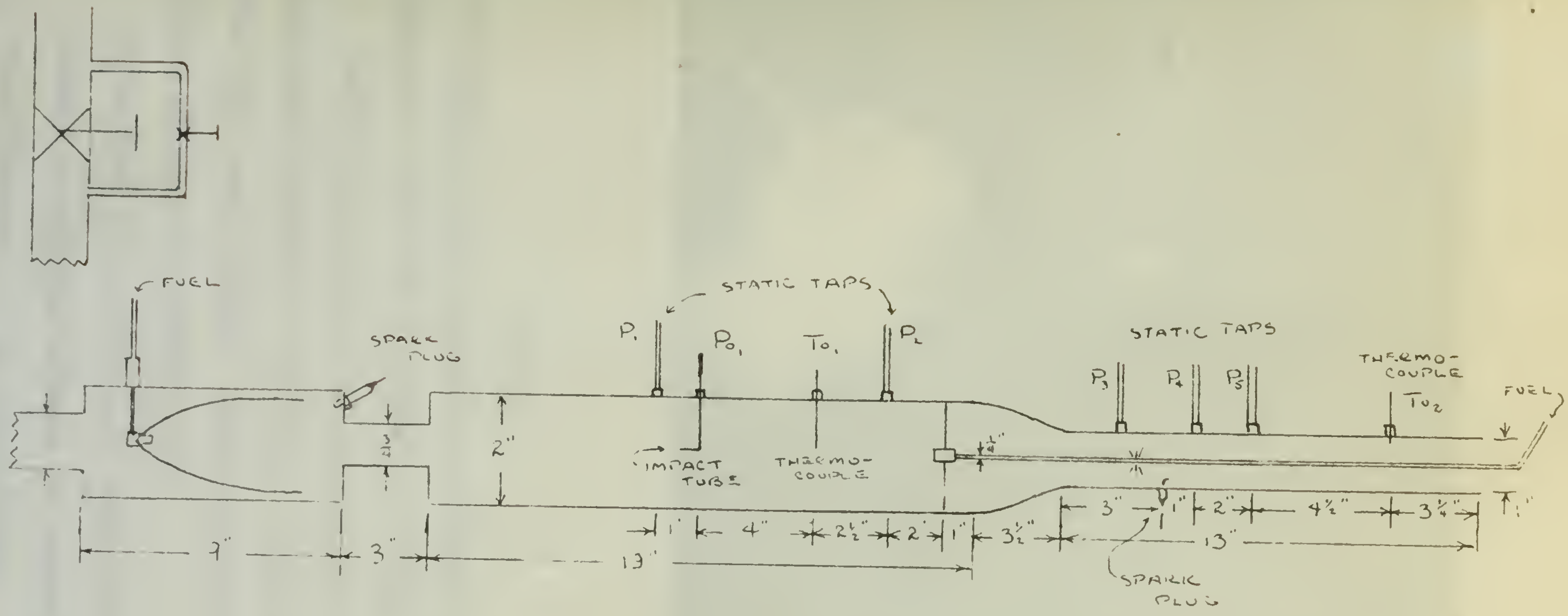
PHOTOGRAPH OF CONSTANT-AREA BURNER AND ATTACHED EQUIPMENT

Constant-area burner to the left, center tube and fuel supply are out of picture.

[illegible]

[illegible]

[illegible]



DIMENSIONS ARE INSIDE DIAMETERS

CONSTANT AREA BURNER

FIGURE 2

FIGURE 3

PHOTOGRAPH OF HIGH VELOCITY INVERTED FLAME

(Exposure - 1/10 sec.; mixture velocity - 50 ft. per sec.)

Smoke was added to the stream by holding a smoking torch near the end of the tube. Torch can be seen in lower left hand corner. Smoke outlines the boundary of mixture stream and outside air.

Note that flame does not touch end of rod.

Stream converges because of volume change at end of rod, then diverges as it decelerates. (See also figure 11.)

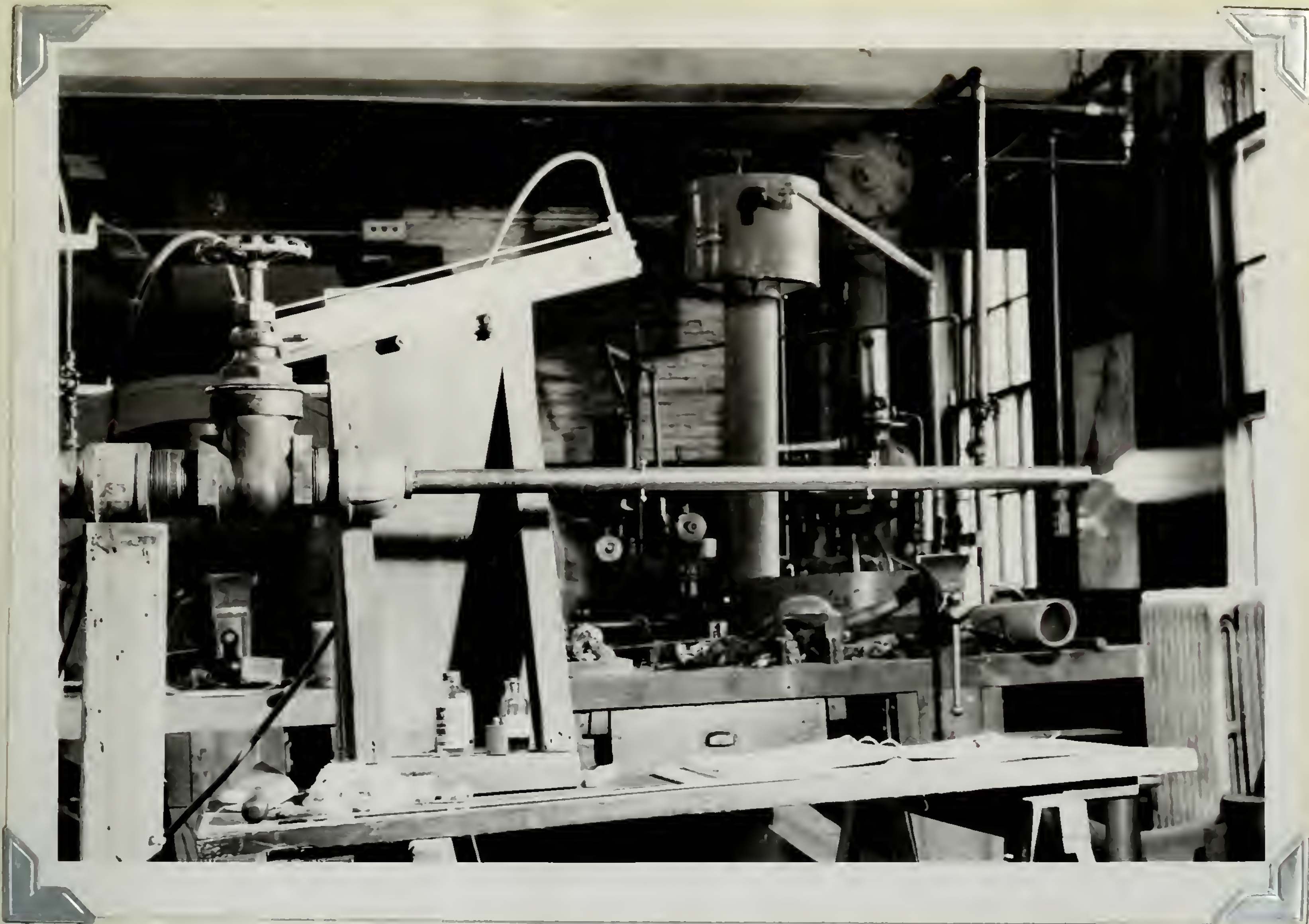


FIGURE 4

PHOTOGRAPH OF INVERTED FLAME EQUIPMENT

Equipment constructed by Lt. Comdr. J. P. Field Jr. and borrowed by the writer for experiments on the inverted flame.

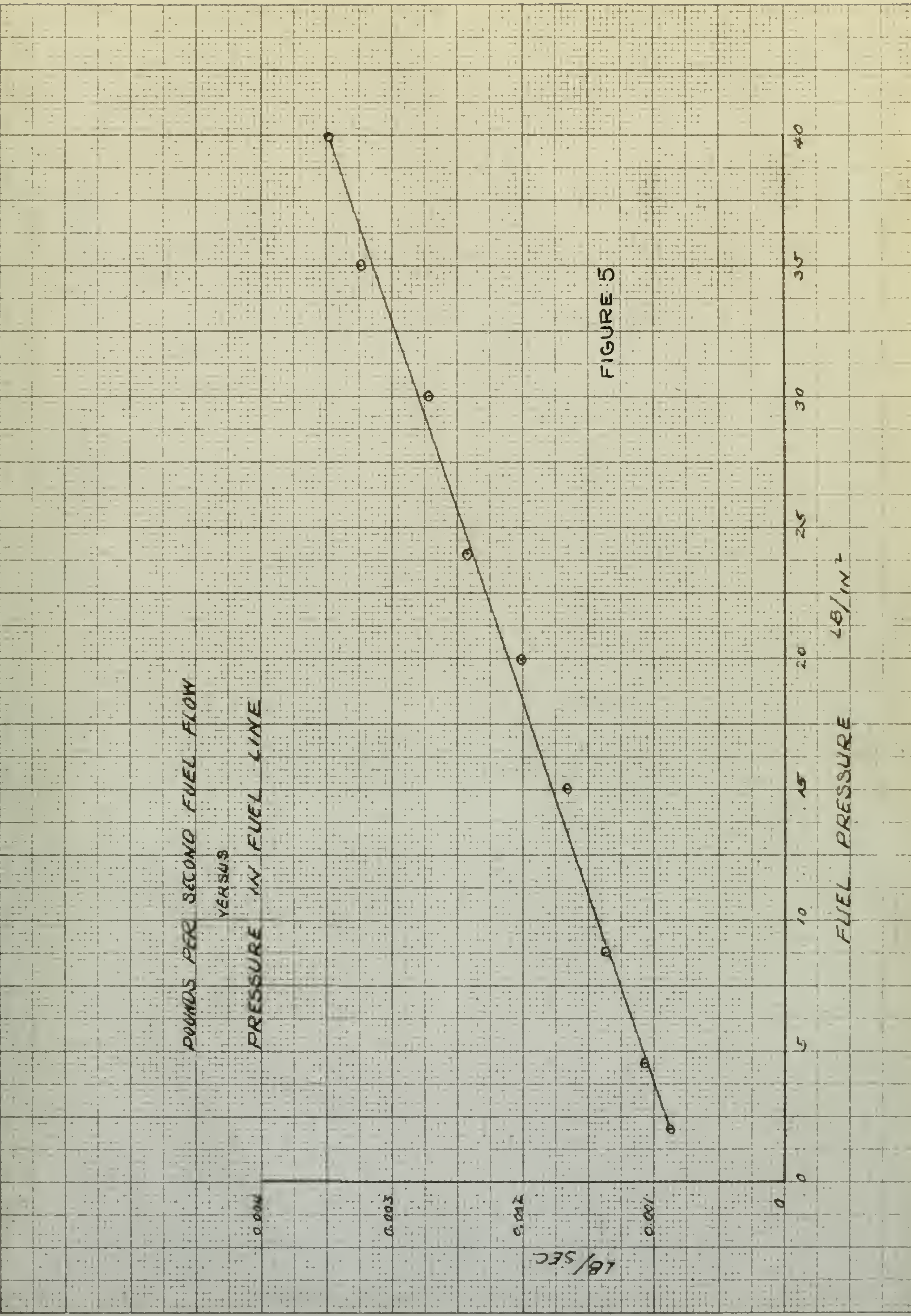
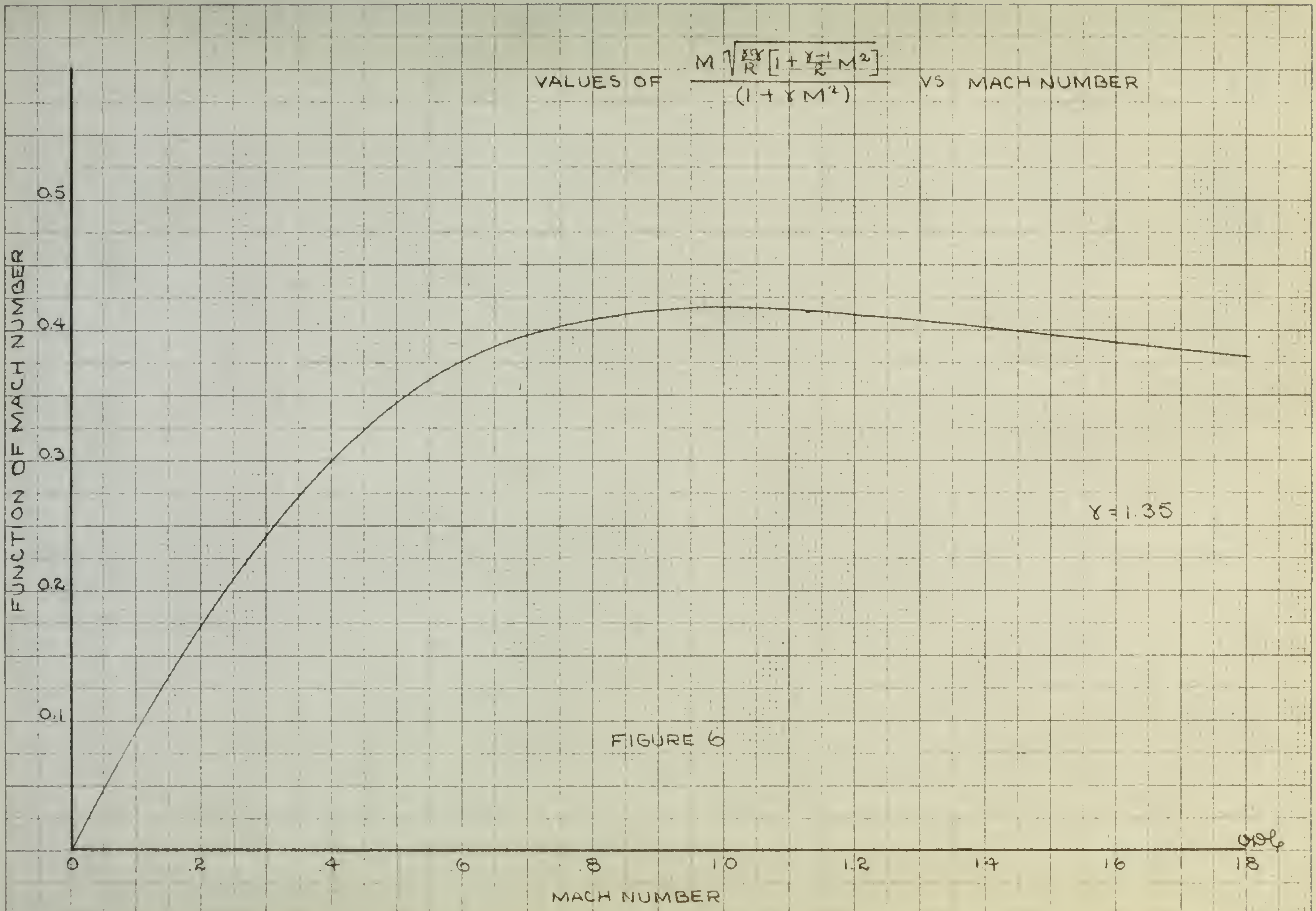

POUNDS PER SECOND FUEL FLOW
VERSUS
PRESSURE IN FUEL LINE
FUEL PRESSURE LB/IN²
LB/SEC
0
0.001
0.002
0.003
0.004
0
5
10
15
20
25
30
35
40

FIGURE 5



VALUES OF $\dfrac{M\sqrt{\frac{g\gamma}{R}\left[1+\frac{\gamma-1}{2}M^2\right]}}{(1+\gamma M^2)}$ VS MACH NUMBER
FUNCTION OF MACH NUMBER
0.5
0.4
0.3
0.2
0.1
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
MACH NUMBER
$\gamma = 1.35$

FIGURE 6

VALUES OF
$\frac{M\sqrt{\frac{\gamma}{2}\left[1+\frac{\gamma-1}{2}M^2\right]}}{(1+\gamma M^2)}$ VS MACH NUMBER
$\gamma = 1.35$
FUNCTION OF MACH NUMBER
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
.02
.04
.06
.08
.10
MACH NUMBER

FIGURE 6-A

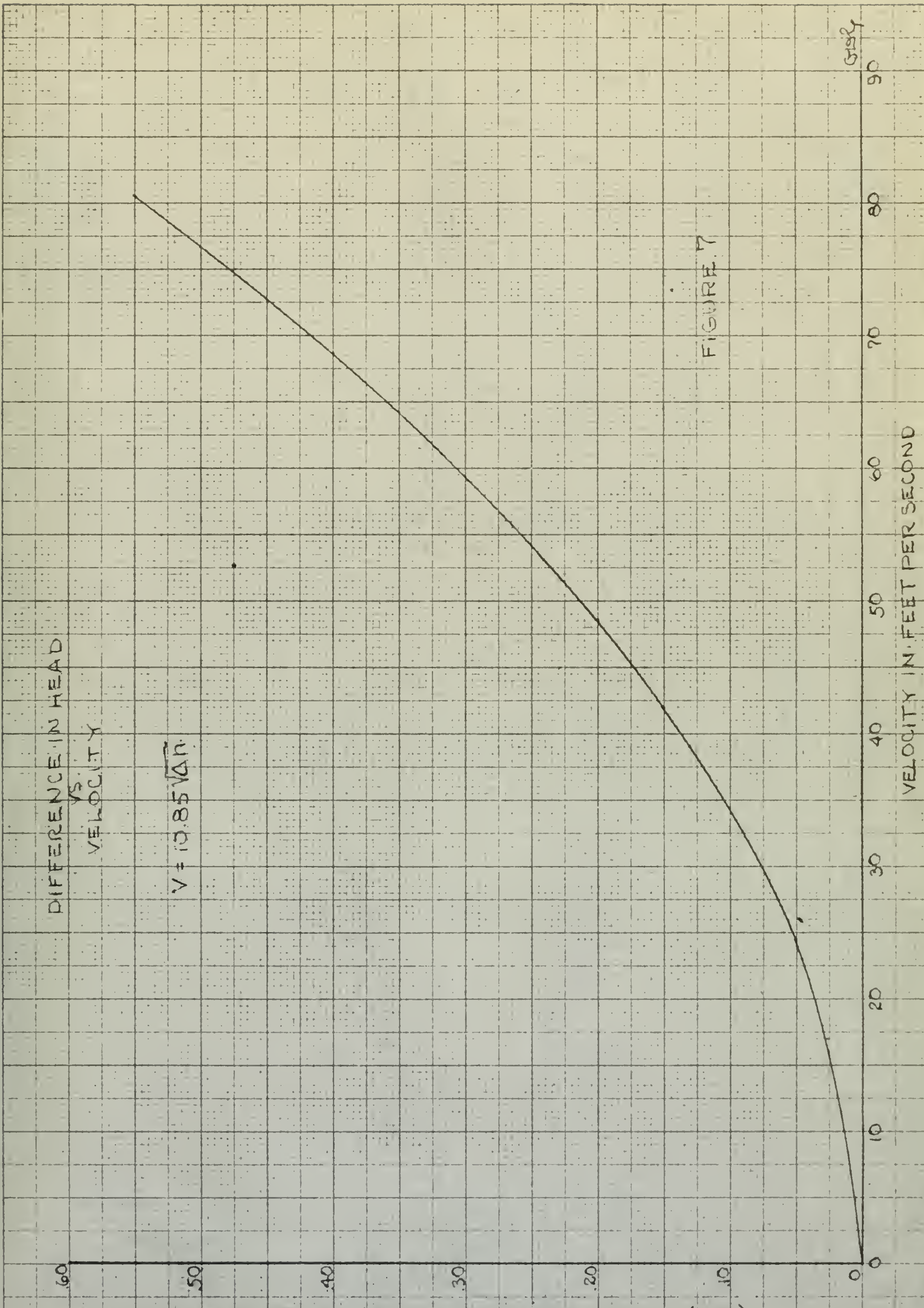

DIFFERENCE IN HEAD
VS.
VELOCITY
$V = 13.85\sqrt{\Delta h}$
VELOCITY IN FEET PER SECOND
0
10
20
30
40
50
60
70
80
90
DIFFERENCE IN HEAD INCHES OF WATER (Δh)
0
.10
.20
.30
.40
.50
.60

FIGURE 7

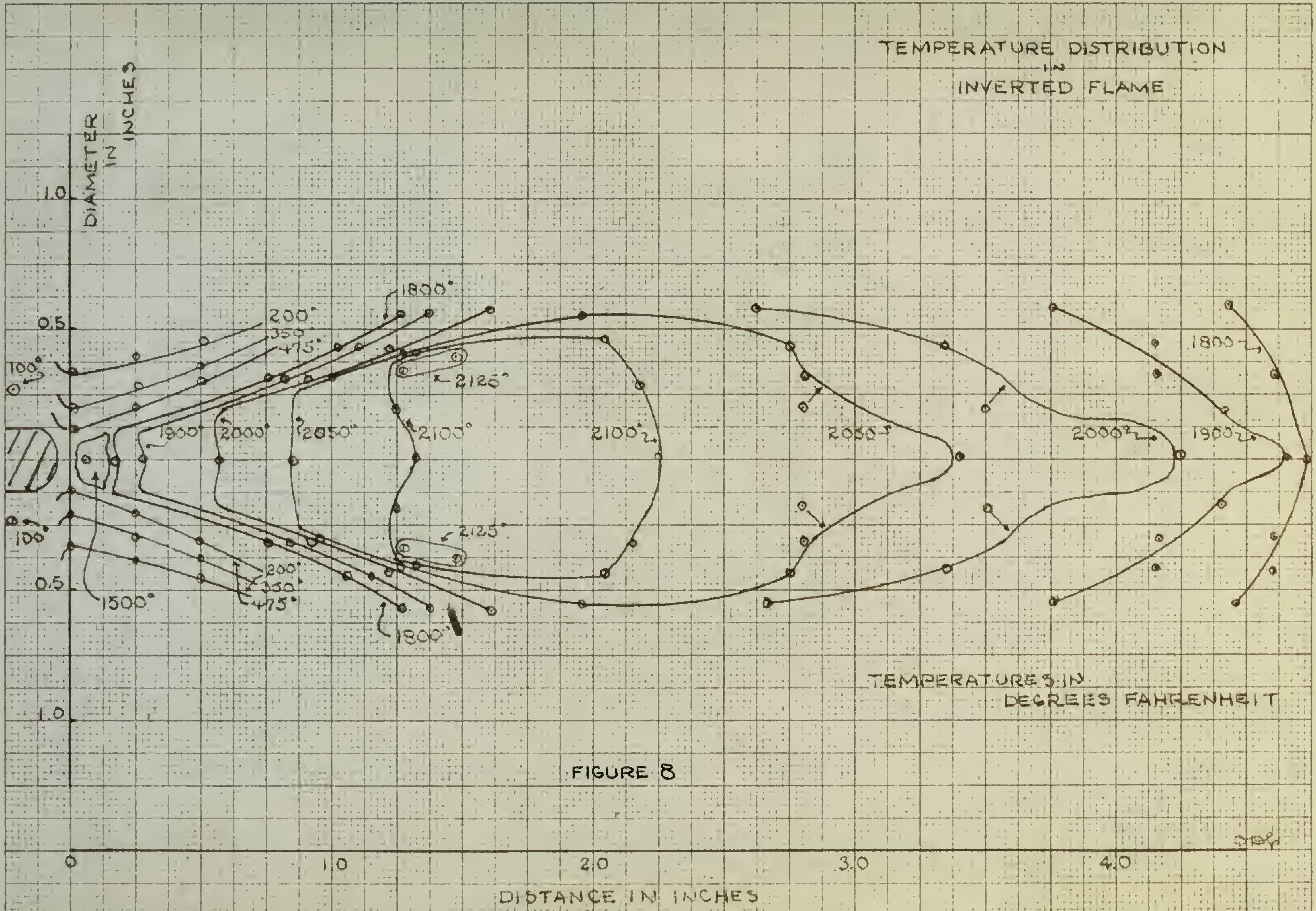
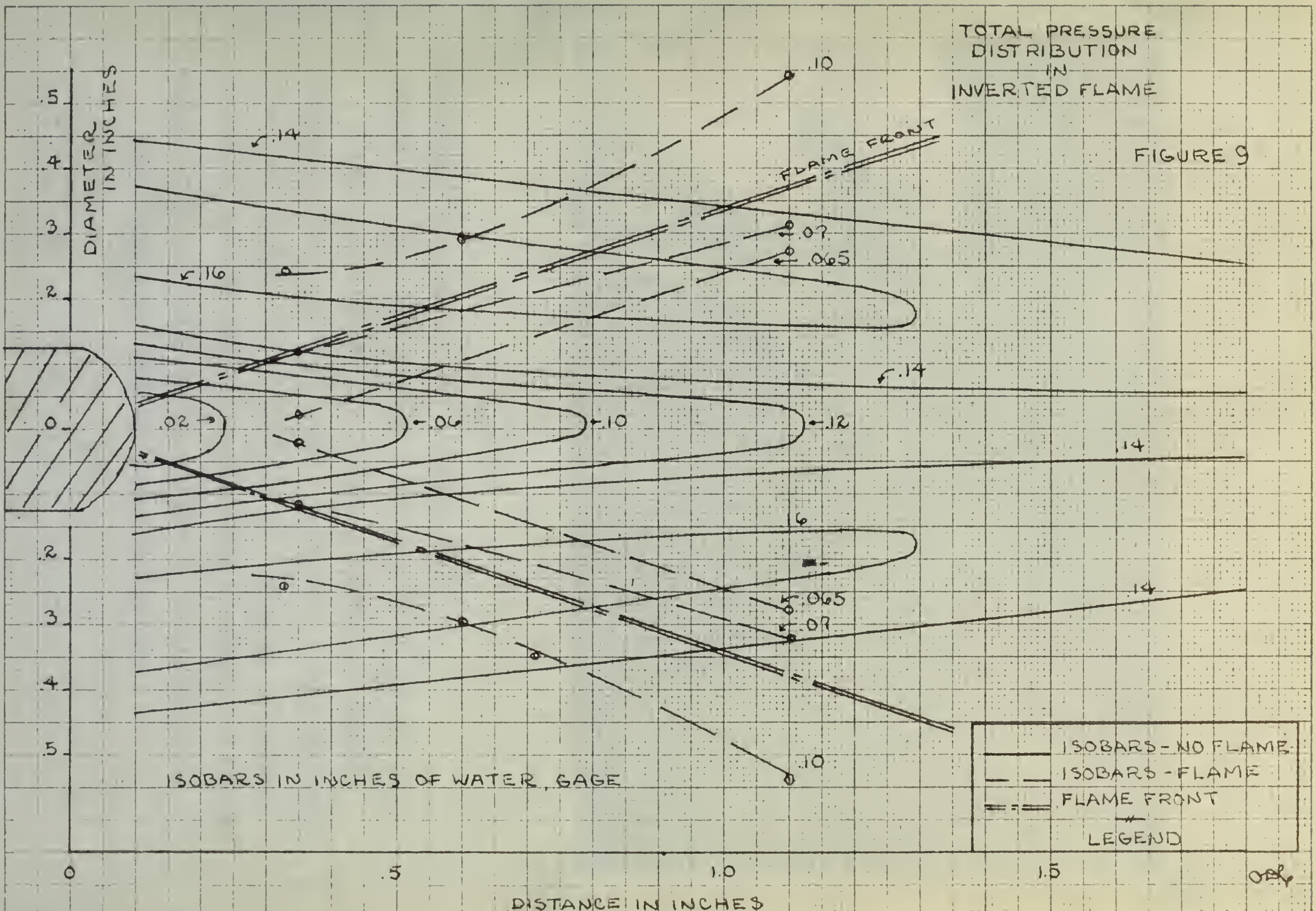

TEMPERATURE DISTRIBUTION
IN
INVERTED FLAME
DIAMETER IN INCHES
1.0
0.5
0.5
1.0
100°
100°
200°
350°
475°
200°
350°
475°
1500°
1800°
1800°
1900°
2000°
2050°
2100°
2125°
2125°
2100°
2050°
2000°
1900°
1800°
TEMPERATURES IN
DEGREES FAHRENHEIT
0
1.0
2.0
3.0
4.0
DISTANCE IN INCHES

FIGURE 8



TOTAL PRESSURE DISTRIBUTION IN INVERTED FLAME

FIGURE 9

FIGURE 10

PHOTOGRAPH OF LOW VELOCITY INVERTED FLAME

(Exposure - 1/10 sec.; mixture velocity - 25 ft. per sec.)

Smoke was added to the stream by holding a smoking torch near the end of the tube. Torch can be seen in lower left hand corner. Smoke outlines the boundary of mixture stream and outside air. Stream converges because of volume change at end of tube, then diverges as it decelerates.

Note that flame does not touch end of rod.

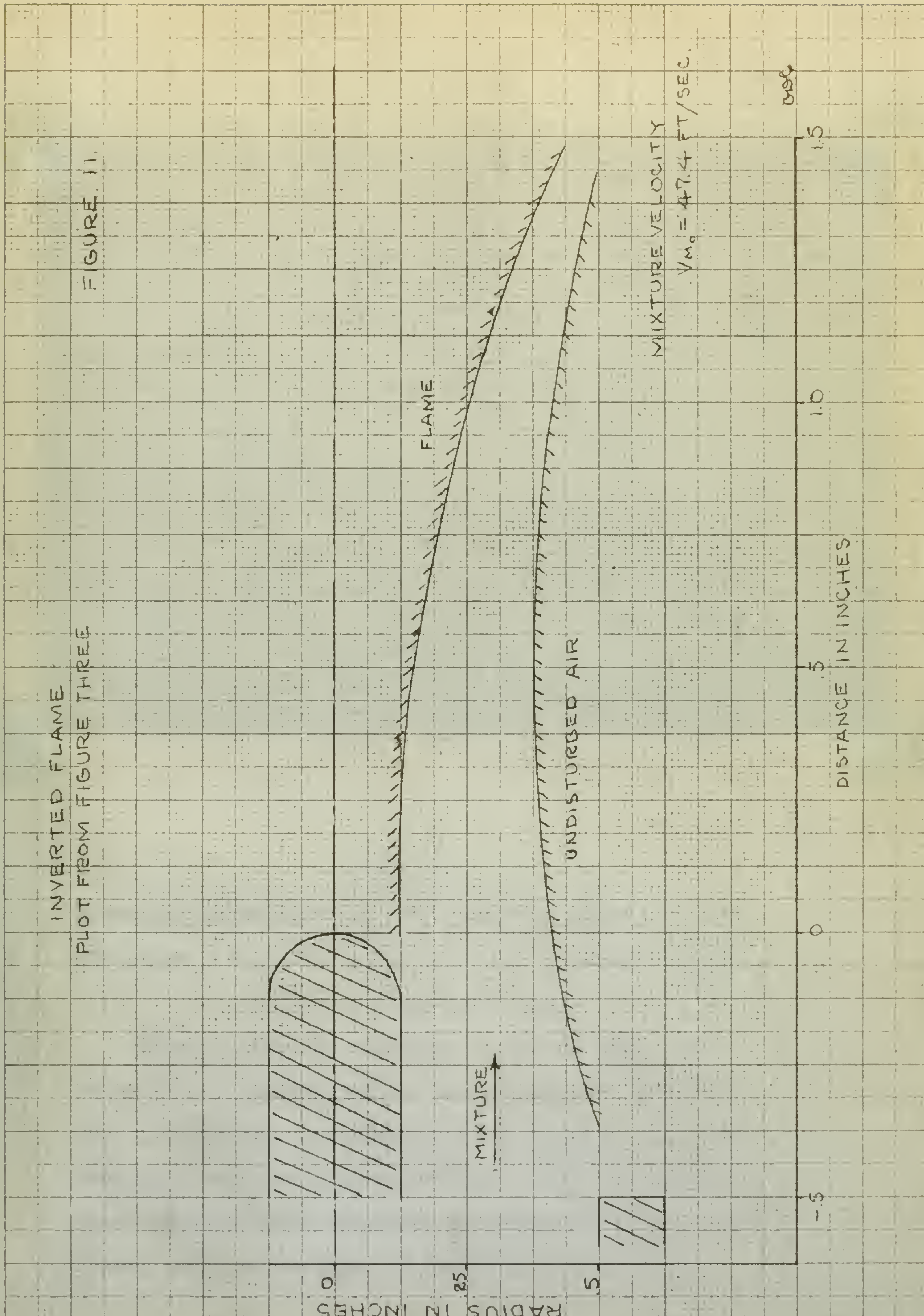


FIGURE 11.
INVERTED FLAME
PLOT FROM FIGURE THREE
MIXTURE VELOCITY
$V_{M_0} = 47.4$ FT/SEC.
FLAME
UNDISTURBED AIR
MIXTURE
RADIUS IN INCHES
0
.25
.5
DISTANCE IN INCHES
-.5
0
.5
1.0
1.5

FIGURE 12

SCHLIEREN PHOTOGRAPH OF LOW VELOCITY INVERTED FLAME

(Exposure - 1/30,000 sec.; mixture velocity - 25 ft. per sec.; flat-ended rod)

Black clouds in vicinity of end of pipe are smoke from ignition torch. Indication of circular flow in ignition zone just off rod tip can be seen. Curvature and turbulence of flame front are apparent. Upper profile shows break-up of flame front into turbulent balls where rest of reaction takes place.

FIGURE 13

SCHLIEREN PHOTOGRAPH OF HIGH VELOCITY INVERTED FLAME

(Exposure - 1/30,000 sec.; mixture velocity - 50 ft. per sec.; flat-ended rod.)

Limits of flame front and mixture stream are clearly defined. Turbulence in flame front is apparent. Straiations in the flame zone are indications of extreme turbulence.

FIGURE 14

SCHLIEREN PHOTOGRAPH - WITHOUT FLAME

(Exposure - 1/30,000 sec.; mixture velocity - 25 ft. per sec.)

Photograph shows diffusion of stream in outside air. Abreast the rod stream shows little turbulence. Turbulence increases with flow distance.

FIGURE 15

INFRA-RED PHOTOGRAPH OF INVERTED FLAME

(Exposure - one second; mixture velocity - 25 ft. per sec.)

Picture was taken on infra-red film with a red filter to exclude all light except from the red end of the spectrum. Purpose was to bring out any part of the reaction zone which was invisible to the naked eye, or to ordinary film. Comparison with other photographs fails to reveal anything in the infra-red film which cannot be seen in the other pictures.

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